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Simulation of the impact of a plastic flyer on an aluminum block using the hydrocode AUTODYN

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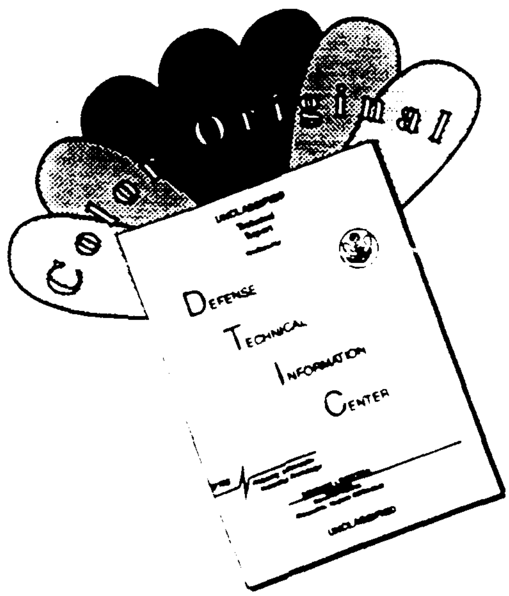

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Summary

At TNO/PML a socalled Mega Ampere Pulser was built to accelerate thin plastic flyers which are subsequently impacted on different target materials. To reach a better understanding of the shape and time development of the shock pulses generated in the target material, a computer simulation of this situation was carried out, using the hydrocode Autodyn. In this report a description is given of set-up and results of the simulation as well as a evaluation of the results and an analysis of the consequences for the experiments.

Samenvatting

Op het PML is een zogenaamde Mega Ampere Pulser gebouwd waarmee kunststof folies worden versneld die vervolgens inslaan op een doelmateriaal. Om inzicht te krijgen in de vorm en de ontwikkeling in de tijd van de in het materiaal opgewekte schokgolven is een simulatie van deze situatie uitgevoerd met behulp van de hydrocode Autodyn. In dit rapport wordt een beschrijving gegeven van de manier waarop de simulatie is opgezet en uitgevoerd en wordt een evaluatie gegeven van de resultaten en een analyse van de konsekwenties hiervan voor de experimenten.

CONTENTS

1 INTRODUCTION

As a part of the ongoing research into the shock sensitivity of explosives and the behaviour of materials under shock loading at the TNO Prins Maurits Laboratory a socalled Mega Ampere Pulser (MAP) was built (see ref. 1)[1]. In this device a high electric current (500 kA - 1 MA) is lead through an aluminum foil during a time interval of approximately 1 μs. As a consequence the foil evaporates instantaneously and forms a plasma of a very high pressure. This plasma is able to punch a flyer out of a plate that lies on top of the foil and to further accelerate it while moving through a barrel. The flyer subsequently impacts on a target material with a very high velocity (in the order of 10 km/s) and generates a short, almost rectangular shock pulse in the material. The height and length of this shock pulse can be varied mutually independently by varying respectively the velocity and the thickness of the flying plate. This property makes the MAP very suitable for the study of the behaviour of explosives and inert materials under short shock loads. The duration of the generated shock pulse however is restricted to approximately 1 μs. For the study of the effects of longer shock waves therefore e.g. a gas gun is needed.

The computerprogram Autodyn is a hydrocode, developed and marketed by the US company Century Dynamics (see ref. 2 and ref. 3). With use of this program shockdynamic calculations can be carried out for all kinds of materials and explosives. One of the strong points of Autodyn is that it is possible with this program to set up and run a simulation interactively, where at any moment the development of any variable can be viewed and the simulation can be adjusted if necessary. At the PML the two-dimensional version of this package has been purchased and has been installed on a Sun Sparcstation 2 workstation. With the two-dimensional version all situations can be calculated that have minimally one symmetry axis or symmetry plane, as e.g. is the case when describing the acceleration of a plastic flyer plate with the MAP.

The purpose of the simulations described in this report is to gain insight into the amplitude and shape of the shock pulse that is generated in the aluminum block on the impact of a plate accelerated with the MAP, and in the time development of the amplitude and shape of the pulse. With use of these results it can be deduced how the measurement results, obtained from experiments with the MAP, should be interpreted in order to derive material properties of inert materials such as the shock Hugoniot and to determine the shock initiation properties of explosive materials.

A second goal of the simulations is to explore the capability of Autodyn to accurately describe this kind of situations and to determine the optimal set-up for the program in order to obtain the best results. In this report only a limited account is given of these aspects of the simulations.

A full description can be found in the Dutch language version of this report (PML-1992-25): Simulatie van de inslag van een kunststof folie op een aluminium blok met behulp van de hydrocode Autodyn).

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1 This research project is part of the assignment A84/KL/147: Detonation trains

2 SET UP OF THE SIMULATIONS

It is to be expected that the high velocity impact of a thin plate on a target material will induce large deformations near the edge of the plate. To give a good description of this phenomenon it will be necessary to use small grid cells in that region and when using a Lagrangian solution method it will be necessary to rezone the grid regularly in order to avoid too large deformations of the grid cells. The consequence is that a single simulation will already take up a considerable amount of time, making a parameter study a lengthy affair. Therefore it was decided to study first a simplified situation and to perform parameter studies and next to carry out a detailed simulation of the impact of a thin plate on an aluminum block and to compare the simulation results with the results of the preceding simulations.

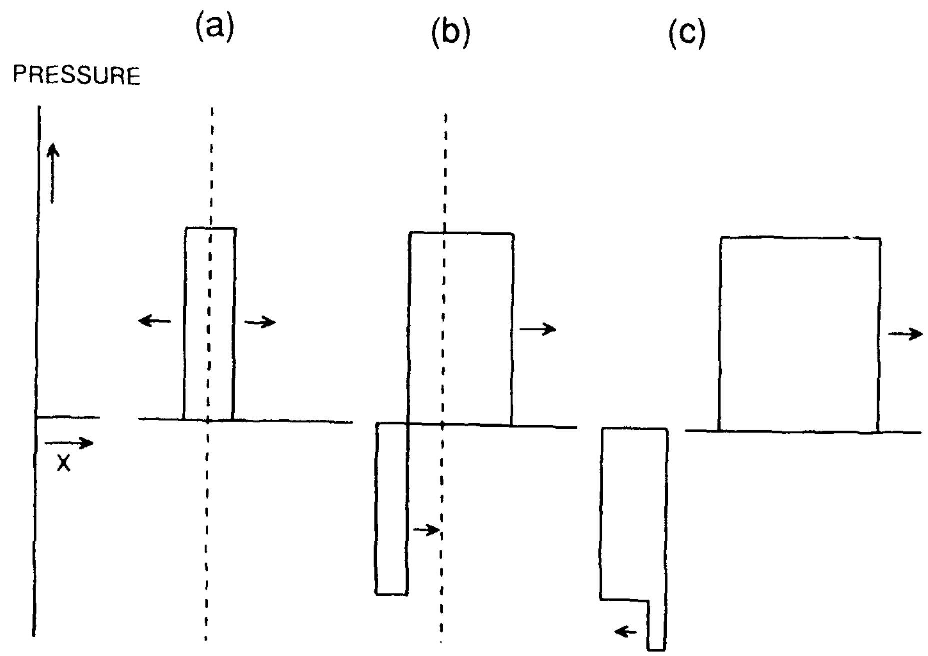

Figure 1 Theoretical development of the shock pulses in block and plate
a) shortly after impact of the plate
b) after reflection of the shock wave at the rear of the plate
c) after reflection of the rarefaction wave at the interface

According to the simple one-dimensional shock theory the following events will occur at the impact of a thin plate on a block (see Figure 1). Both in the block and in the plate a shock wave will be generated, moving away from the interface of plate and block (Figure 1a). The shock wave in the plate will reflect at the rear of the plate and will next propagate as a rarefaction wave towards the

interface (Figure 1b). When the rarefaction wave reaches the interface the shock wave in the block will be terminated abruptly while also the contact between plate and block will be lost (Figure 1c). According to this theory an almost rectangular shock pulse will be generated in the block. The length of the pulse is proportional to the velocity of the plate and its height is equal to the time needed for a shock pulse to travel up and down the plate and is therefore proportional to the thickness of the plate.
In connection with the above at first the simplified situation has been studied of the propagation of a one-dimensional rectangular shock wave in an aluminum block. This implies that deviations of the rectangular shape of the shock wave have not been taken into consideration nor the influence of two-dimensional effects like the rarefaction waves travelling inwards from the edge of the impact crater. After having performed parameter variations in this simplified simulation next a more realistic simulation has been performed and its results have been compared with the preceding simulations.

3 THE PROPAGATION OF A RECTANGULAR SHOCK WAVE IN AN ALUMINUM BLOCK

3.1 Set up of the simulations

In the simulations a rectangular grid was used with an axial symmetry. In the radial direction 20 cells were used and in the axial direction the number of cells varied between 50 and 400. The radial dimension of the grid was 4.5 mm and its length varied between 2.5 mm and 10 mm. The grid was filled with the material Al2024, present in the Autodyn library, with its default material constants. To keep the simulation semi-one-dimensional the radial velocity was forced to zero by imposing the boundary condition $v_y = 0$ along the outer boundary of the block. A shock wave in the material was generated by imposing a pressure boundary condition at the front of the block during a certain period. The length of the shock pulse varied between 25 ns and 100 ns and its amplitude between 10 GPa and 85 GPa.
Since in the first calculations rather strong pressure oscillations showed up, it was first investigated how the oscillations could be eliminated without affecting the development in time of the pressure pulse. To this end the values of the artificial viscosity coefficient and axial cell length were varied. Next the influence of variations in the height and length of the pulse were investigated. In Table 1a list is given of the performed calculations with the values of the varied parameters.

Table 1 Values of the varied parameters and several results for the performed simulations

simulation nr.	pulse height (GPa)	pulse length (ns)	cellsize (μm)	lin. visc. coeff.	oscill-ations	t_0 (ns)	α
P4	85	100	100	0.2	yes	304	0.704
P5	85	100	100	0.4	yes	259	0.665
P6	85	100	100	0.8	no	228	0.637
P7	85	100	100	0.1	yes	278	0.654
P10	85	100	200	0.2	yes	253	0.611
P11	85	100	200	0.4	yes	272	0.684
P12	85	100	200	0.6	yes	241	0.664
P13	85	100	200	0.8	no	209	0.629
P14	85	100	50	0.2	no	291	0.679
P15	85	100	50	0.4	no	285	0.699
P16	85	100	25	0.2	no	310	0.718
P17	20	100	50	0.2	no	446	0.544
P18	85	50	25	0.2	no	149	0.696
P19	85	25	12.5	0.2	no	74	0.701
P20	85	25	25	0.2	no	68	0.673
P21	60	100	50	0.2	no	310	0.660
P22	40	100	50	0.2	no	362	0.643
P23	10	100	50	0.2	no	623	0.465

3.2 Results

The first simulations were used to determine the most appropriate values of the viscosity coefficient and the cell size in order to avoid numerical oscillations without affecting the shock pulse. It appeared that the best method was to leave the viscosity coefficient at its default value and to choose the cell size in such a way that the shock pulse was covered by at least 20 cells. In the following calculations therefore the ratio between pulse length and cell length was fixed at a value of 20.

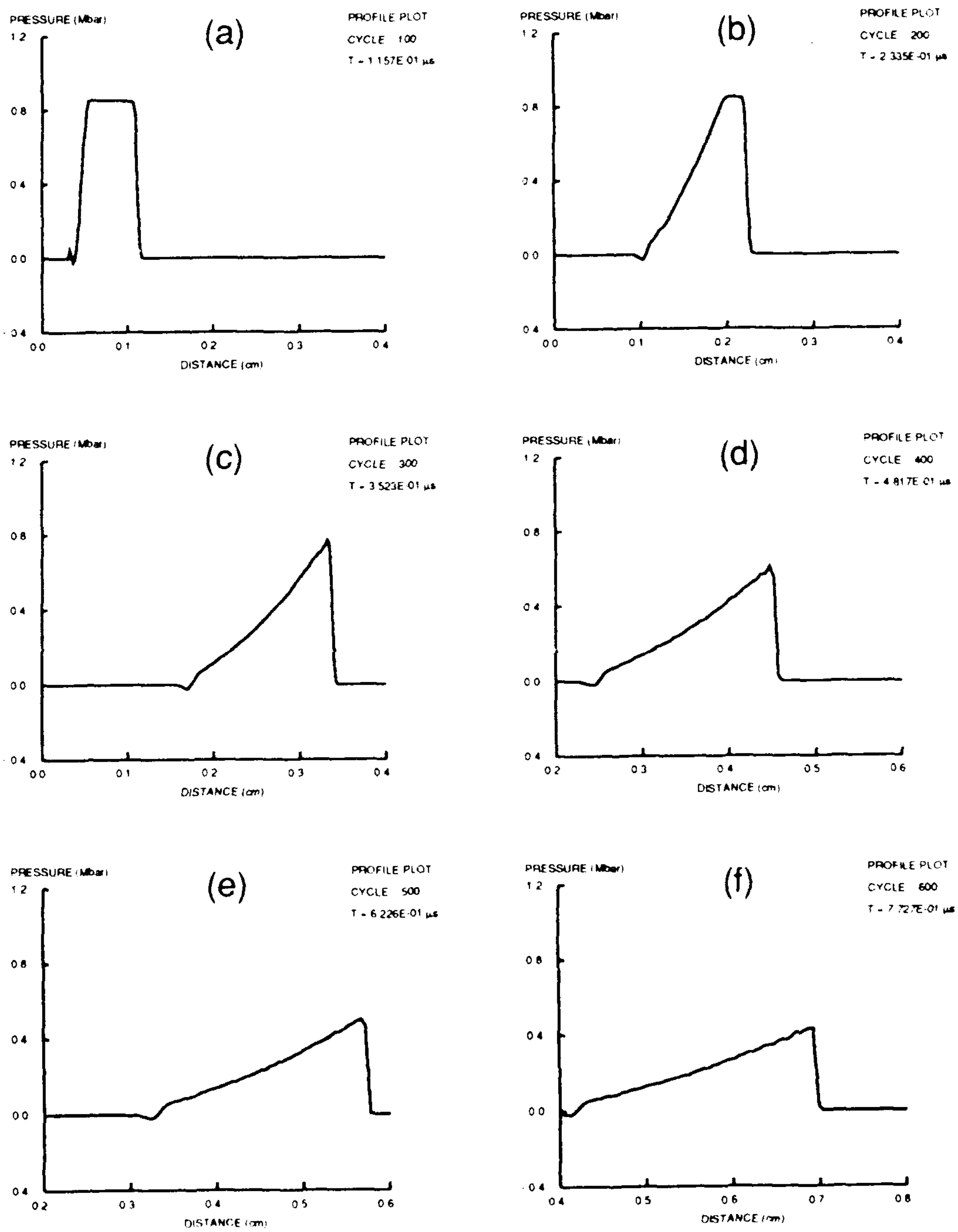

Figure 2 Pressure profiles in simulation P16 at various points of time

In Figure 2 an example is given of the time development of the shock pulse for one of the simulations. In the figures it can be seen how the initially rectangular pulse is gradually

transformed into a triangular one by the influence of the rarefaction waves that originate at the rear of the pulse and that gain on the shock front (see Figure 2a and Figure 2b). After the rarefaction waves have overtaken the shock front the amplitude of the wave decreases while the length of the pulse steadily increases (see Figures 2c, 2d, 2e, 2f). The same process can be seen in Figure 3 that gives the development of the pressure as a function of time for 10 equidistant points at the axis of the block. From this figure it can be clearly seen that the rate at which the amplitude decreases after the overtaking of the shock front by the rarefaction waves is initially rather high but after that steadily decreases.

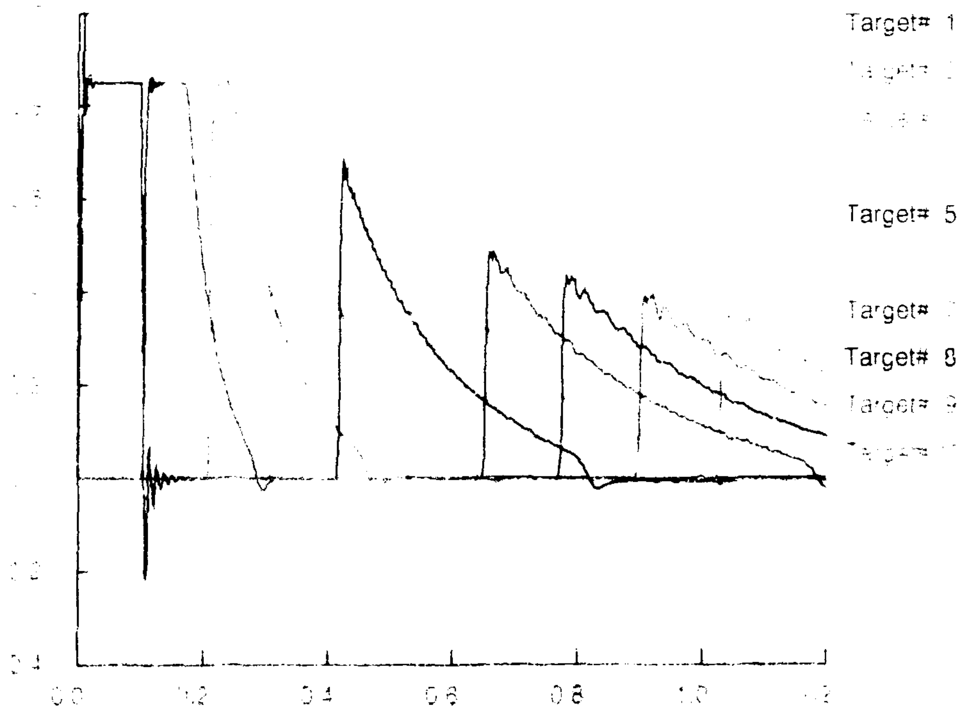

Figure 3 Pressure as a function of time for 10 points along the axis of the block at a distance of 0, 1, 2, 3, 4, 5, 6, 7, 8 and 9 mm from the front of the block for simulation P16

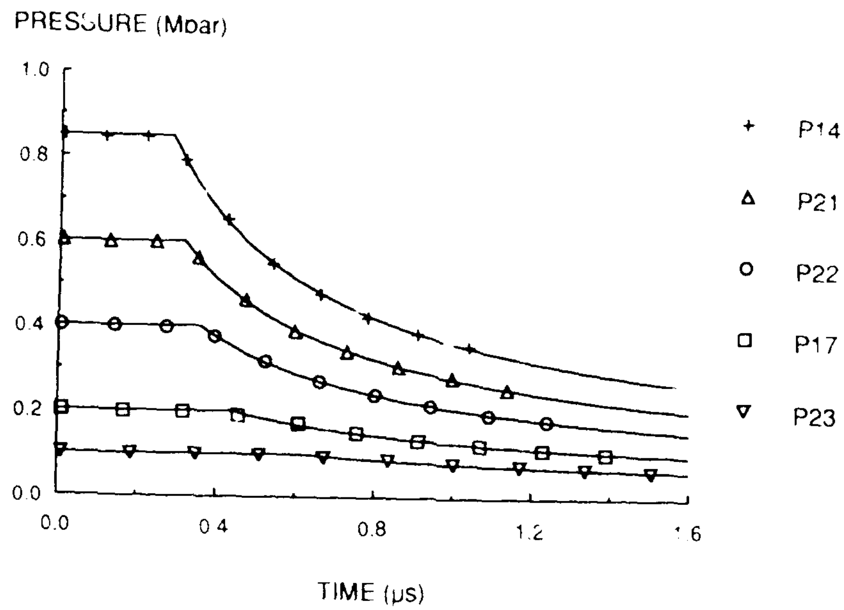

Figure 4 Maximum values of the pressure for the points of Figure 3 as a function of the point of time at which that pressure is attained for 5 different values of the pulse height

In Figure 4 an overview is given of the results of 5 simulations where the only difference was the initial pulse height. In this figure the value of the maximum pressure for the equidistant points along the axis mentioned earlier, is plotted against the point of time at which that value of the pressure is reached. The curves in the figure all have the same shape but the point of time where the decrease of the shock amplitude sets in is clearly later for lower shock amplitudes. A similar combination of simulation results is given in Figure 5, where the results are shown for 3 simulations with a different pulse length.

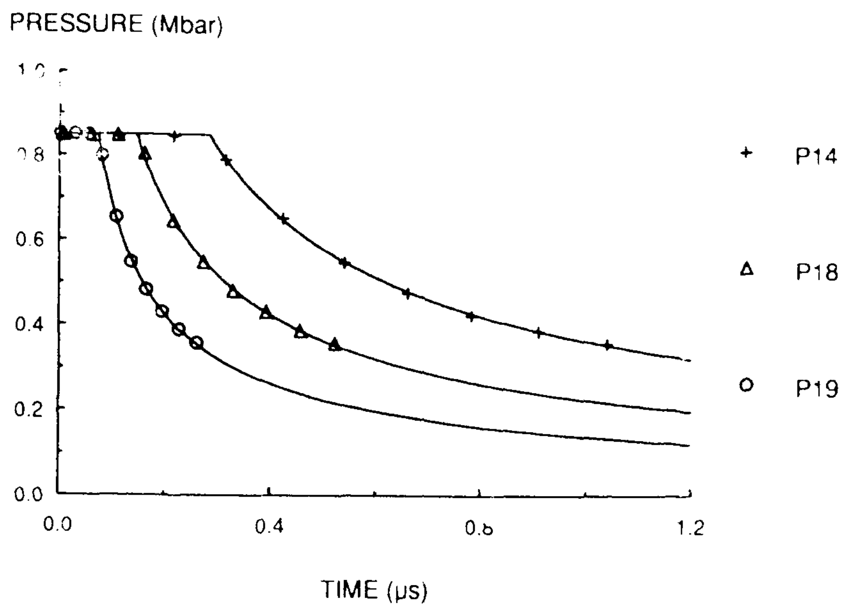

Figure 5 Maximum values of the pressure for the points of Figure 3 as a function of the point of time at which that pressure is attained for 3 different values of the pulse length

3.3 Analysis of the results

The analysis of the results described in the previous section produced a remarkable result. From the application of regression analysis to the part of the curves where the pressure decreases it namely appeared that this part of the curves can be described extremely well by the universal function: $P = P_0 (t/t_0)^{-\alpha}$, where P_0 is the starting value of the pressure and t_0 is the point of time at which the pressure starts decreasing. The correlation with this function is remarkably high; the correlation coefficient always exceeds a value of 0.995 except for simulation P23 where the coefficient has a value of 0.992. As can be seen from Table 1 the parameter has an almost constant value of 0.67 ± 0.03 with the exception of simulations P17 and P23, where the shock pressure was respectively 20 and 10 GPa.

Theoretically it is not yet clear why the damping of the shock pulse can be described so remarkably well by the formula $P = P_0 (t/t_0)^{-\alpha}$ for shock pulses above 20 GPa. The fact that the pressure decrease depends on the total length of time that the pulse is propagating and not on the length of time elapsed since the start of the decrease of the amplitude, indicates that the damping is due to the continuous influence of rarefaction waves that, originating at the rear of the pulse, overtake the front. It would be interesting to investigate theoretically to which degree the damping can be

accurately described by such a simple function and what is the influence of the initial shape of the pulse. The value found for the coefficient α is remarkably close to the value 2/3. This might have a theoretical background but could also be an accident, while the value might also be related to a material constant. The latter possibility might be examined by performing simulations with other materials.

4 THE SIMULATION OF THE IMPACT OF A KAPTON PLATE ON AN ALUMINUM BLOCK

4.1 Set-up of the simulation

One calculation has been carried out simulating the impact of a kapton plate on an aluminum block with an impact velocity of 9 mm/μs. The kapton plate had a diameter of 9 mm and was 125 μm thick, the aluminum block had a diameter of 15 mm and was initially 500 μm thick. As was the case in the simulations described earlier an axial symmetry was used and use was made of the Lagrange processor. The direction of motion of the plate was parallel to the axis. For the kapton plate 25 cells were used in the axial direction and 90 cells in the radial direction. In the radial direction the cell size was varied in such a way that it was comparable in size to the axial cell size in those regions where strong deformations of the cells were expected to occur and up to 30 times larger in other regions.

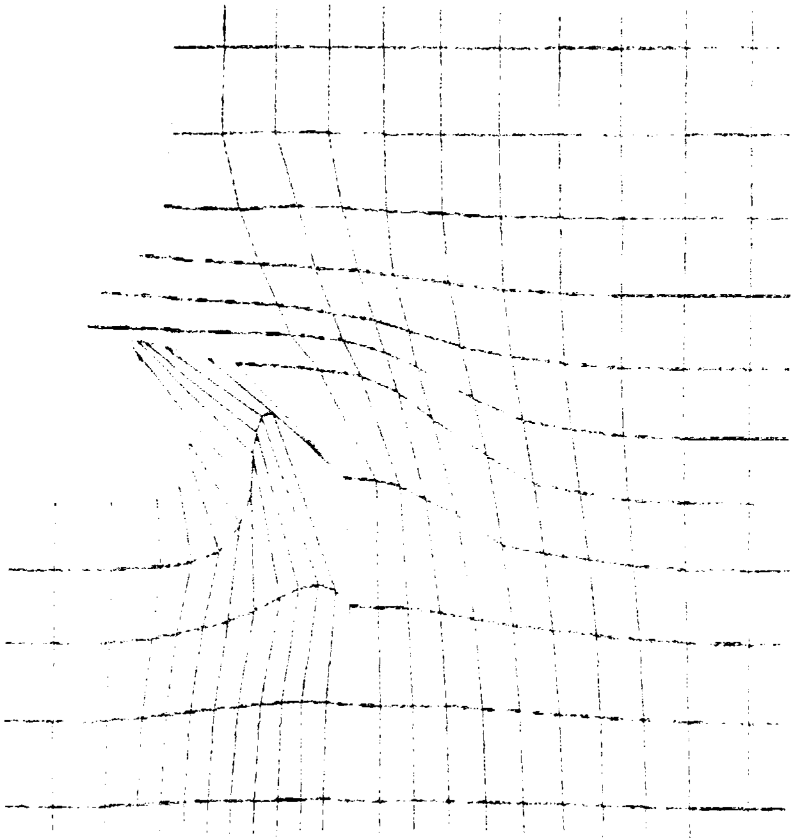

Figure 6 Deformation of the grid near the edge of the kapton plate after 5.01 ns

For the aluminum block 50 cells were used in the axial direction and 150 cells in the radial direction. The axial cell size varied between 5 µm at the interface with the kapton plate to 17 µm at the rear of the block. The distribution of the cell size in the radial direction was equal to that used for the kapton plate. The length of the aluminum block was initially kept short (500 µm) to economize on the total number of cells. During the simulation at a certain moment a block with a length of 200 µm (10 cells) was added to the aluminum block and in a later stage the length of the block was enlarged to 3 mm, where the number of cells was kept the same (60 in the axial direction) and the grid was rezoned.

To describe the interaction between the kapton plate and the aluminum block use was made of the impact/slide interaction mechanism, incorporated in Autodyn. To reduce the problems with the deformation of the grid a small artificial friction was introduced between the two materials with a value of 0.1 near the edge of the plate (here a value of 0 stands for no friction and a value of 1 for infinite friction).

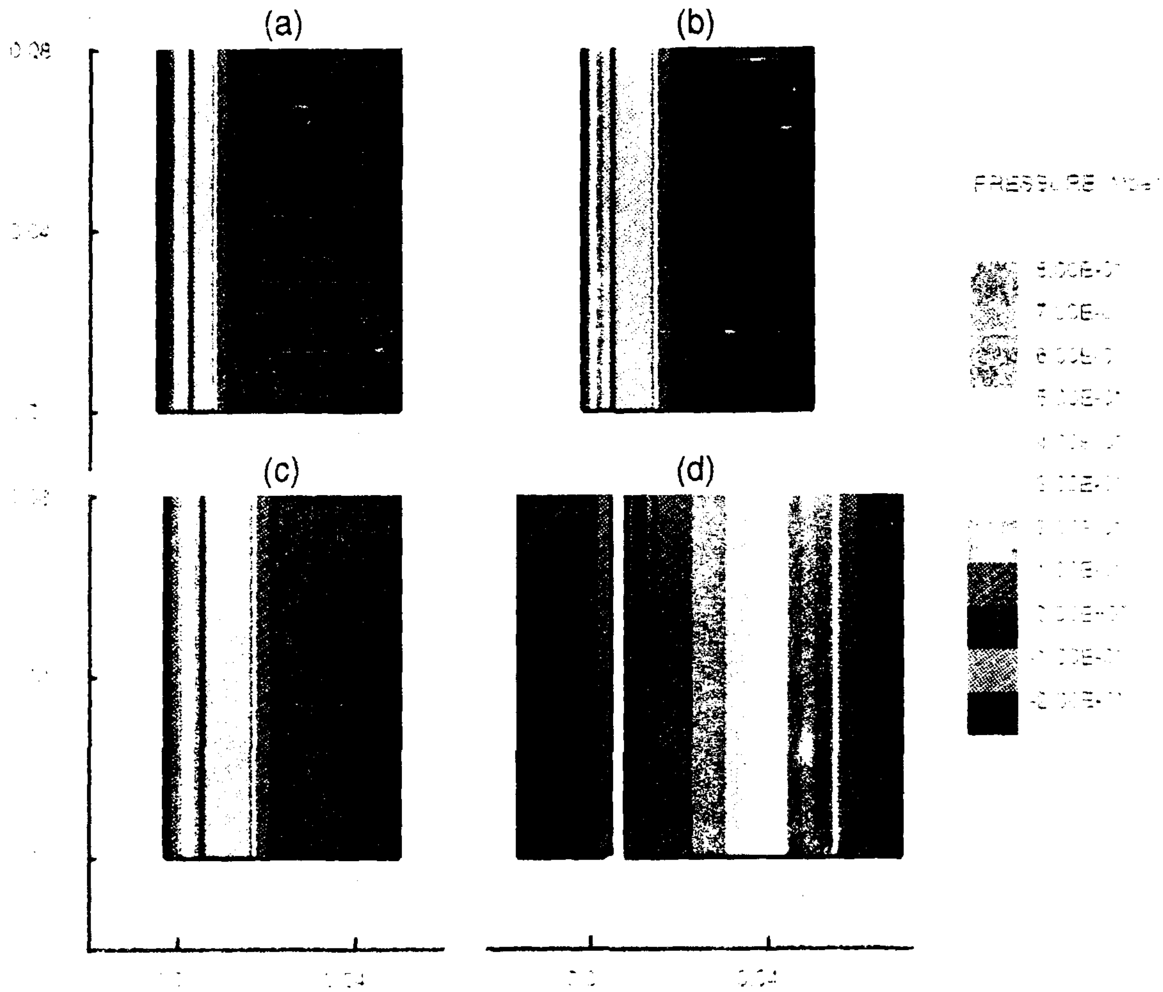

Figure 7 Pressure profiles near the axis of the kapton plate

a) the shock wave has traversed half of the kapton plate
b) the shock wave has reflected at the rear surface of the plate
c) the shock wave has reached the interface again
d) the plate and the aluminum block have separated again

4.2 Results

As expected in the simulations strong deformations of the grid occurred near the edge of the plate. In the aluminum block a wire-edge was formed while also the material at the top of the plate formed a sharp edge. In Figure 6 as an example the deformation of the grid after 50 cycles is shown . To prevent the cells from deforming to such an extent that the timestep in the calculation would become too small and from degenerating (i.e. two non-adjacent sides of a cell intersect), it was necessary to

regularly adjust the grid in this region. This rezoning process can be performed interactively and fast in Autodyn but still considerably slows down the progress of the calculation.

The development of the pressure profiles initially conformed to the expectations, expressed in Figure 1. After the moment of impact in both materials pressure waves of equal amplitude started to propagate in opposite directions. Figure 7a shows the pressure profiles near the axis at a point of time that the shock wave has traversed half of the kapton plate. In Figure 7b and 7c the pressure profiles are shown respectively at some time after the shock wave has reflected at the rear surface of the plate and at the moment that the shock wave has reached the interface with the aluminum block. It appears that at its reflection at the free surface of the kapton plate the shock wave did not change sign as abruptly as expected. The pressure decreased only gradually and hardly became negative and it also took longer than expected before the kapton plate and the aluminum block separated again . Eventually this did happen as can be seen in Figure 7d.

The graduality of the pressure decrease can also be seen in Figure 8 where the development of the pressure is shown as a function of time for 5 equidistant points in the kapton plate. As a consequence of this shock behaviour also the pulse generated in the aluminum block is not as rectangular as originally assumed (see Figure 9).

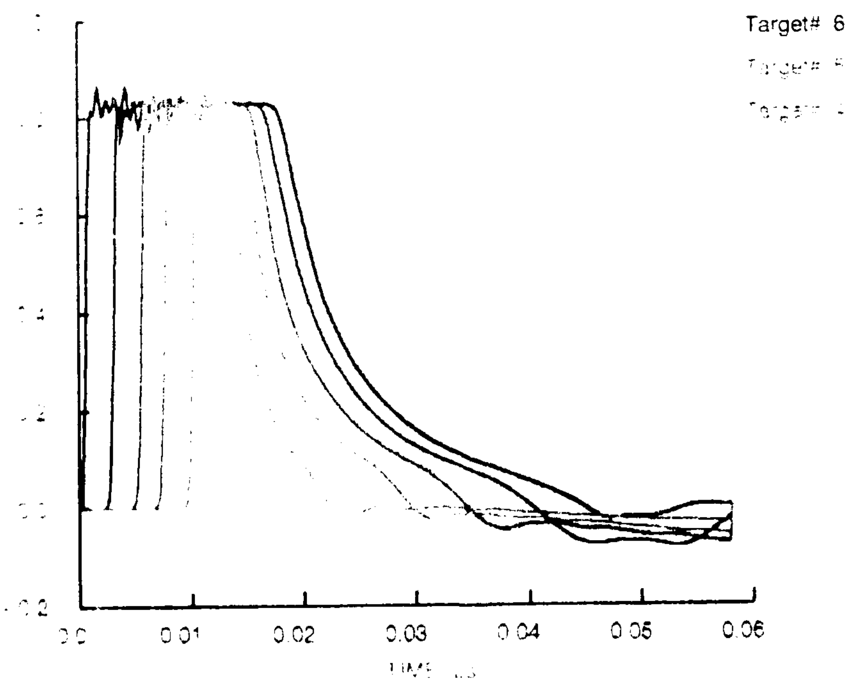

Figure 8 **Time development of the pressure for 5 points in the kapton plate, located at a distance of respectively 1, 25, 50, 75 and 100 μm from the interface**

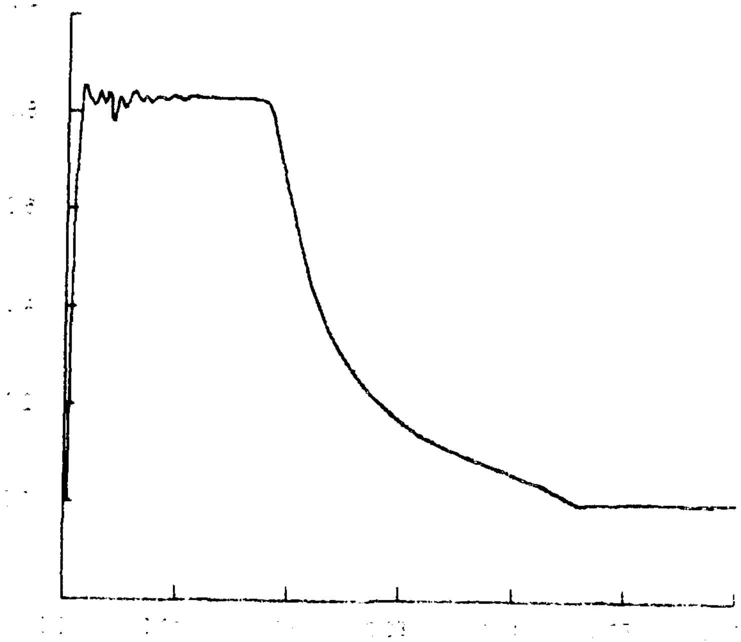

Figure 9 Shape of the shock wave, generated in the aluminum block by the impact of the kapton plate

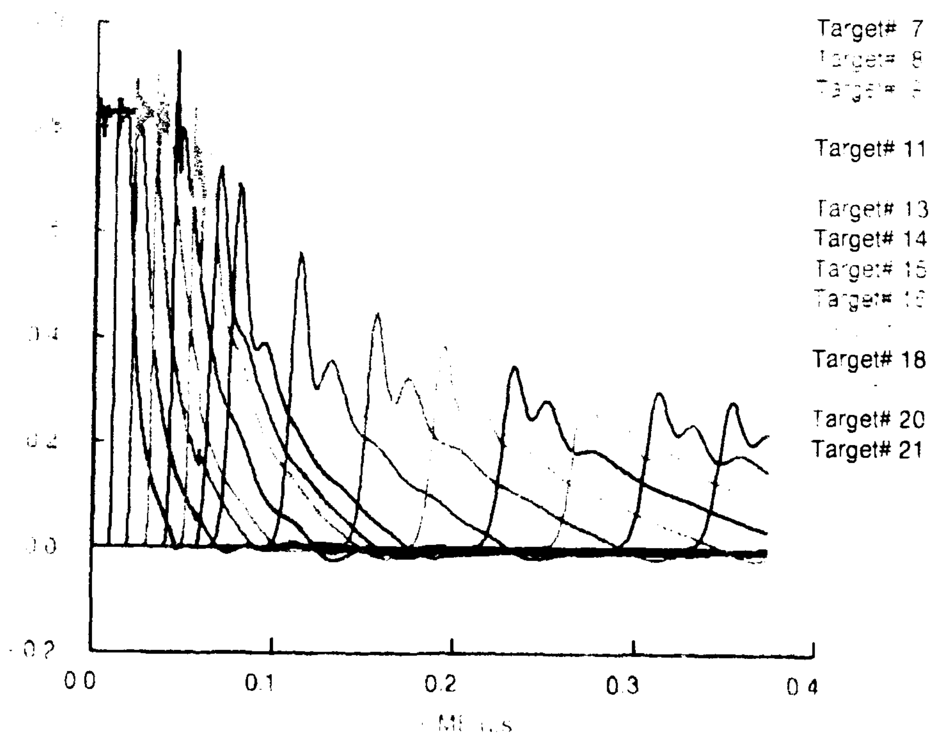

Figure 10 Time development of the pressure for 15 points in the aluminum block, located at a distance of respectively 1, 100, 200, 300, 400, 500, 600, 700, 1000, 1300, 1600, 1900, 2200, 2500 and 2800 μm from the interface

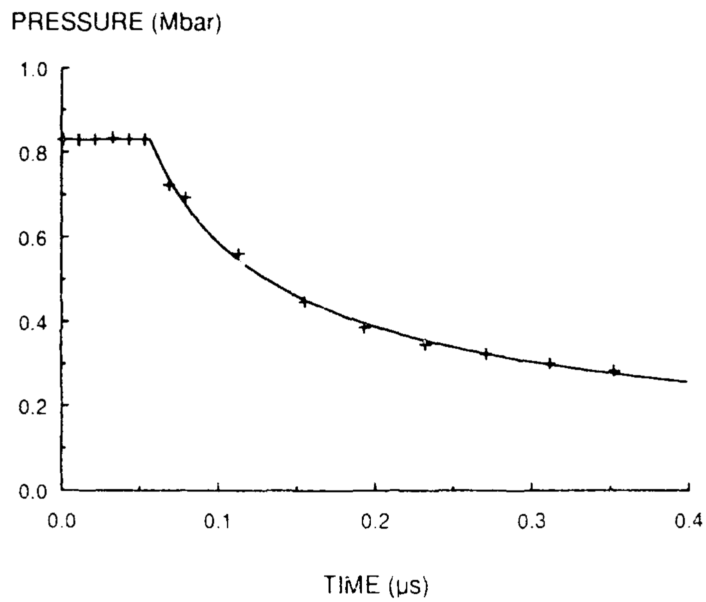

Figure 11 Maximum values of the attained pressure for the points in Figure 10 as a function of the point of time that pressure value was attained

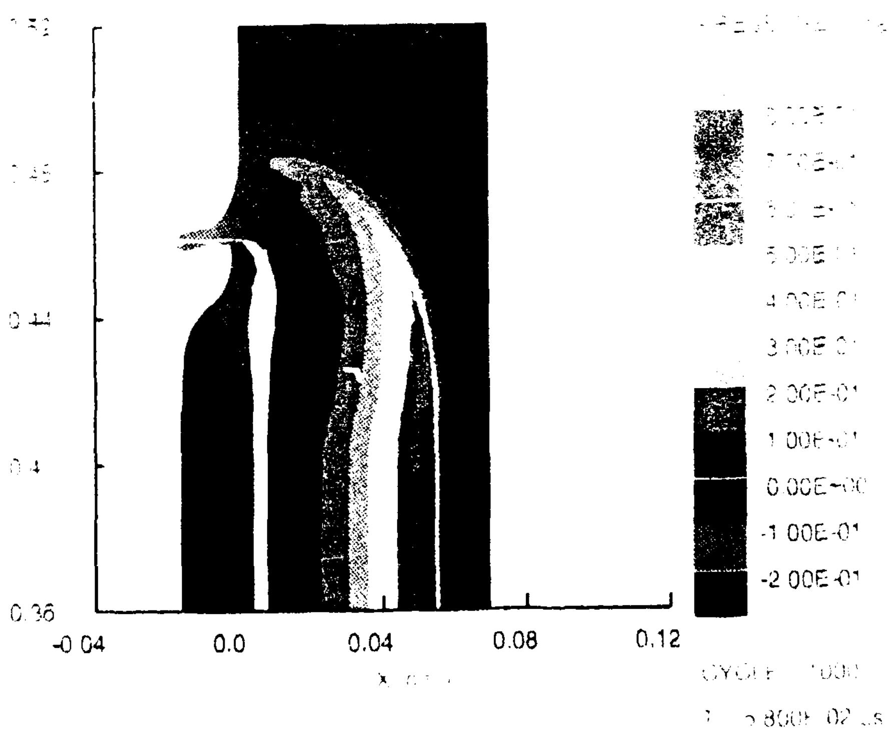

Figure 12 **Pressure profiles near the edge of the plate at the moment that plate and block have been separated again**

The further development of the shape of the shock pulse was analogous to the development of the pulses in section 3.2. Figure 10 shows the time development of the pressure for a number of points at the axis of the block. Although the picture is somewhat blurred by the occurrence of rather strong oscillations it can still be clearly observed that the pressure development is in conformance with the earlier simulations. In Figure 11 the maximum pressure attained at these points has again been plotted as a function of the point of time that this value was reached. Also in this case the data could be approximated very well by the formula $P = P_0 (t/t_0)^{-\alpha}$. Here the values of t_0 and α are respectively 57 ns and 0.60. The somewhat low value of α compared to the earlier results might be a consequence of the fact that the shock pulse, generated in the block, is not as rectangular as in the earlier cases.

The time development of the pressure profiles near the edge of the kapton plate naturally showed a much more complex pattern as a consequence of the two-dimensional effects occurring in that region. In Figure 12 the pressure profiles are shown at the moment that the plate and the block have been separated again. From the figure it can be seen that the shock waves have also expanded outwards in the radial direction and on the other hand that rarefaction waves have penetrated into the material and are proceeding towards the axis. The further development of these processes is shown in Figure 13 where the shock pulse has advanced approximately 3 millimeters in the block. At this stage the rarefaction waves have come 2 millimeters closer to the axis. At a later stage they will reach the axis and they will then give an extra contribution to the damping shown in Figures 10 and 11. The calculations however have not been proceeded up to this point.

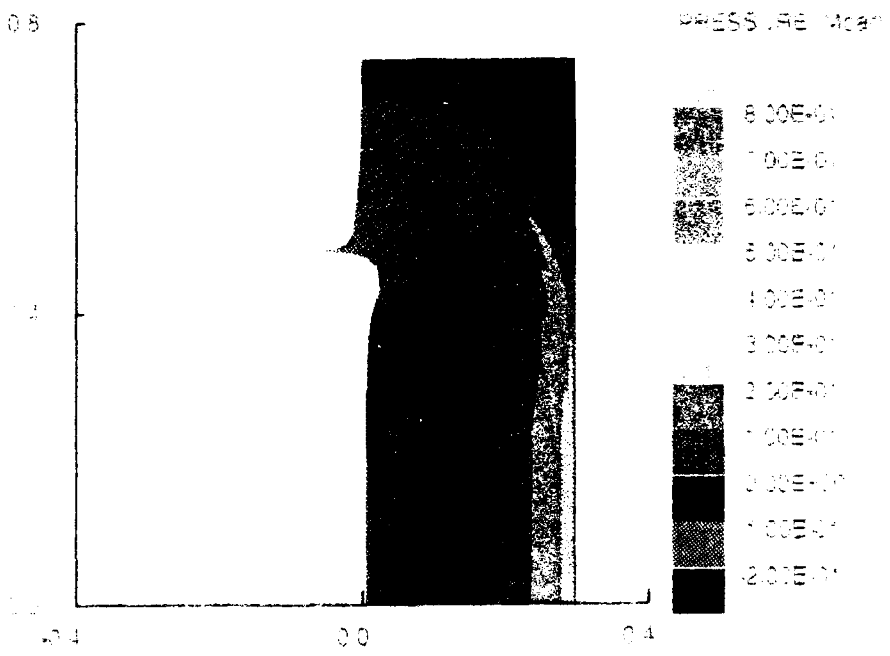

Figure 13 Pressure profiles in the aluminum block at the moment that the shock wave has advanced almost 3 mm in the block

4.3 Analysis of the results

In this simulation it appeared that on reflection of the shock wave at the free surface of the kapton plate the pressure changed sign at a much slower rate and reached much less low values than had been expected beforehand. It will have to be examined whether this expectation was justified after all or whether the set-up of the simulation was not adequate to describe the reflection of such a shock wave. Possibly the number of cells in the plate should be enlarged.

As a consequence of this reflection behaviour the shock pulse generated in the aluminum block was less rectangular at its tail than expected. The time development of the shock pulse near the axis however was fully analogous to the development of the pulses observed in section 3.2, the only difference being that the value of the damping constant was slightly lower. This can be explained qualitatively by the presence of the extra tail at the rear of the pulse. The rarefaction waves, originating at the rear of the pulse, namely need more time to overtake the front, resulting in a

lower damping. Whether this explanation can also provide a good quantitative description of the results requires further theoretical and numerical investigations.

The two-dimensional aspects of the simulation seem to have occurred in accordance with the expectations. The shock waves have expanded outwards, albeit with strong damping, and the rarefaction waves have propagated inwards with the expected speed. How close to the physical reality the results of this simulation really are will have to appear from an comparison with experimental observations.

5 DISCUSSION

The simulations described here were carried out to gain a good insight into the shape and time development of shock pulses in an aluminum block, generated by the impact of a kapton flyer plate that was accelerated with the MAP. In this respect the simulations have fulfilled their purpose; it even appeared that the damping of a rectangular shock wave could be described by a remarkably simple and general formula. To which degree this formula is really generally applicable and what is its background will need some further investigations. Another point that is not yet understood is the way in which the shock wave in the kapton plate reflects at the free surface. Also this point will need some further investigations.

From the results of these simulations we can draw the conclusion that it will be difficult to measure the shock Hugoniots of inert materials with use of the MAP. The shock amplitude namely will start to decrease strongly within a distance of a few millimeters from the interface. This makes it difficult to measure the shock parameters of the pulse by means of a number of measuring probes, mounted at discrete locations. On the other hand, if the shock damping can indeed be described in a reliable way by a universal formula, it might be possible to obtain a reasonably reliable determination of the shock parameters by interpolation and extrapolation of the measured values.

When investigating the sensivity for shock initiation of explosive materials with the MAP it will again have to be taken into account that the assumption that the explosive is struck by a rectangular shock wave is in principle only valid for the first few millimeters. In practice the shock wave will often be enhanced instead of damped by the influence of the chemical reactions that occur in the first layers of the explosive, but in which degree and at which point of time this occurs depends on the properties of the explosive and the amplitude of the shock. At the analysis of shock initiation experiments with the MAP one should therefore take good account of the limited validity of the assumption that the inert shock pulse has a rectangular shape.

6 CONCLUSION

With the hydrocode Autodyn simulations have been carried out of the impact of a kapton foil at an aluminum block. From the simulations it appeared that the almost rectangular pulses generated in the block loose their block shape within a few millimeters and next show a strong decrease in amplitude. It appeared possible to describe this decrease for high shock pressures with a remarkably simple formula: $P = P_0 \, (t/t_0)^{-\alpha}$ in which t_0 is the point of time that the pulse looses its rectangular shape and the damping coefficient α has an almost constant value of 0.67. Further investigations will be needed to determine how correct and generally applicable this formula is and what is its background. Another point that needs further investigation is whether the shock wave behaviour in the kapton plate has been described correctly, since this has a strong influence on the shape of the tail of the shock pulse generated in the aluminum block.

At the analysis of experiments performed with the MAP for the determination of shock Hugoniots and shock initiation properties of explosives one will have to take well into account the conclusion drawn from the outcome of the simulations that the generated rectangular pulse will transform into a triangular one within a few millimeters and will next strongly decrease in amplitude.

7 AUTHENTICATION

H.J. Verbeek
(project manager/author)

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Simulation of the impact of a plastic flyer on an aluminium block using the hydrocode AUTODYN
(Simulatie van de inslag van een kunststof olie op een aluminium blok met behulp van de hydrocode AUTODYN)

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14. SUPPLEMENTARY NOTES

15. ABSTRACT (MAXIMUM 200 WORDS (1044 BYTE))

At TNO/PML a socalled Mega Ampere Pulser was built to accelerate thin plastic flyers which are subsequently impacted on different target materials. To reach a better understanding of the shape and time development of the shock pulses generated in the target material, a computer simulation of this situation was carried out, using the hydrocode Autodyn. In this report a description is given of set-up and results of the simulation as well as a evaluation of the results and an analysis of the consequences for the experiments.

16. DESCRIPTORS		IDENTIFIERS
Acceleration	Shock Waves	
Plastic Foils	Computerized Simulation	
Impact	Computer Programs	
Targets		
Aluminium		

17A. SECURITY CLASSIFICATION (OF REPORT)	17B. SECURITY CLASSIFICATION (OF PAGE)	17C. SECURITY CLASSIFICATION (OF ABSTRACT)
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18. DISTRIBUTION AVAILABILITY STATEMENT	17D. SECURITY CLASSIFICATION (OF TITLES)
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